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STATIC AND DYNAMIC TESTS OF STEEL FRAME STRUCTURES INTO THE INELASTIC RANGE OF DEFORMATION

by

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Final Report to
RESEARCH DIRECTORATE
AIR FORCE SPECIAL WEAPONS CENTER
Air Research and Development Command
Contract AF 33(616)-170
Project 1080
Task 10803

UNIVERSITY OF ILLINOIS
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FINAL REPORT

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Approved by

N. M. Newmark

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Department of Civil Engineering

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RESEARCH DIRECTORATE
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Kirtland Air Force Base, New Mexico

Project : 1080
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STATIC AND DYNAMIC TESTS OF STEEL FRAME STRUCTURES INTO THE INELASTIC RANGE OF DEFORMATION

I. INTRODUCTION

1. Purpose and Scope

The purpose of the program which has been conducted at the University of Illinois under Contract AF 33(616)-170, Task 10803, Project 1080, can be stated in general terms as "the performance of tests and analyses to obtain basic information concerning the behavior of steel structural frames and elements when subjected to known static and dynamic loadings that produce extensive inelastic deformations."

The project was begun in July of 1952 and, in its various phases, has been carried on continuously since then. During this time three Final Reports[*1, 3, 9] have been written. However, since this is to be the last Final Report on the contract, the entire project will be summarized. The review of such an extensive program must necessarily be cursory; however, it is hoped that this presentation will provide the reader with enough information to permit his understanding the investigation as regards its purpose, scope, results produced and their applicability to problems pertaining to the inelastic behavior of steel frame structures.

2. Acknowledgments

The investigation described in this report was performed by staff members of the University of Illinois in cooperation with the Wright Air

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* The numbers refer to entries in the Bibliography presented at the end of the text.

Development Center and the Air Force Special Weapons Center, Department of the Air Force, under Contract AF 33(616)-170 as Task 10803, Project 1080.

The project was conducted in the Structural Research Laboratory of the Department of Civil Engineering under the general direction of N. M. Newmark, Professor of Civil Engineering and Head of the Department. Project supervisors have been, in chronological order; G. K. Sinnamon, Research Assistant Professor of Civil Engineering; F. L. Howland, Research Associate in Civil Engineering; and J. M. Massard, Research Assistant Professor of Civil Engineering.

The many research assistants and research associates who have been associated directly with the project include R. J. Munz, R. J. Mayerjak, W. Egger, R. F. Wojcieszak, J. H. Sams, C. L. Wilkinson, L. W. Heilmann, A. Ang, and D. McDonald.

One Technical Report produced with project funds was based upon a doctoral dissertation by W. J. Hall.

The instrumentation used throughout the investigation was, in general, the responsibility of V. J. McDonald, Research Assistant Professor of Civil Engineering. In addition to those individuals named many other members of the staff of the University of Illinois have aided the advancement of the program. Not the least of these were the personnel of the Civil Engineering Shop, and the many student helpers employed to perform the routine computational work necessary.

II. CONCLUSIONS

1. Comment

The conclusions described below were reached as the result of tests performed under the following conditions. The material in all cases was mild structural steel which nominally met the requirements of ASTM Specification A7 - 56T. All of the tests were performed at room temperature and at rates which were either "slow" (maximum load and deflection reached in several minutes, or a few hours in some cases) or "rapid" (maximums reached in times on the order of fifteen to fifty milliseconds). The configurations of the test systems were such that specimen resistances were not limited by buckling of any type until the maximum strains were well into the range of strain hardening. All failures were ductile; i.e., no brittle fractures.

2. Conclusions

1. The actual resistance of a mild steel structural element to an imposed inelastic deformation increases with the rate of that deformation, and is also dependent upon the time involved.[7, 8, 9, 11]

2. In most of the specimen types in which it occurred, local inelastic buckling was less pronounced in the rapid tests than in the slow ones, which indicates that the effectiveness of the beam section was increased with the rapidity of deformation.[5, 8, 11]

3. An axial load on a structural member decreases the ability of the member to resist lateral load, but does not affect appreciably the total resistance of the member to an external moment except in the limited range of deformation immediately following initial yielding.[3, 6, 8, 11]

4. The effect of shear upon the moment capacity of an 8 WF 58 section loaded laterally and slowly in the plane of the major axis was found to be negligible even for a beam having an equivalent cantilever span to depth ratio as low as two. However, in a region of constant shear but gradient moment, the development of a general shear yielding condition in the web caused deflections considerably greater than those which resulted from concentrated yielding primarily caused by moment.[2]

5. In most of the structural elements and models tested, the initial "elastic" region of the resistance-deflection relationship had a slope less than that derived using elementary theory and assumed ideal conditions of support.

6. A static resistance-deflection function for a simple structural element or a relatively simple structure can be determined with good accuracy by using practicable approximations to relate strains to deflections, and then computing resistance on the basis of the known static stress-strain characteristics of the material involved.[1, 3, 4]

7. For research purposes requiring good accuracy, an equivalent resistance-deflection function for a relatively simply structure subjected to rapid deformation can be determined in a manner similar to that mentioned above using, of course, the dynamic properties of the material in the determination of the resistance. The procedure should be such that the equivalent resistance is computed using instantaneous material stresses at the critical sections which are compatible with the strains, straining rates, and times involved. The total resistance so determined (which does not include inertia forces) is actually a function of time and velocity as well as displacement (as was indicated in paragraph II.2.1), and, therefore, is

strictly valid only for the particular case considered, or for others very similar as regards loading function and structural configuration.[11]

8. However, since the effect of delayed yielding is probably important only in cases of short duration impulse, and the general yielding resistance of mild steel is relatively insensitive to changes of straining rates within one or two orders of magnitude, suitable accuracy can be obtained in most practical problems (where the dynamic loading function is seldom known with great accuracy) simply by increasing the static inelastic resistance of the structure (as determined by use of the procedure outlined in paragraph II.2.6) in accordance with the straining rates estimated to exist at critical locations in the structure as it responds to the rapid loading imposed.[7, 8, 9]

9. Methods were developed for analyzing indeterminate frame structures deformed inelastically.[8, 10] In these procedures the resisting moments throughout the structure which correspond to a compatible deflection configuration are determined. The methods are illustrated with the solution of "static" problems. However, they could be used with slight modification in the timewise step-by-step solution of problems involving structural response under rapid loading. Their use in this manner would be most practicable with the use of a high speed digital computer.

10. The analytical procedures which have been developed on this program were intended for use in research applications.[3, 4, 8, 10, 11] However, they should be useful not only in the planning of testing programs and the evaluation of experimental results but also in determining the relative accuracy of simpler methods which are more suitable for purposes of design and routine analysis.

III. GENERAL COMMENTS

1. General Comments

The experimental studies made under Contract AF 33(616)-170 to obtain basic information concerning structural behavior and for correlation with the analytical studies were inevitably of relatively narrow scope compared with the entire range of structural usage. However, the results of the program are applicable, at least indirectly, to much of the field which the studies were intended to cover, the effect of blast loadings on structures. The major omissions in the program were tests of connections other than the rigid welded ones used, and tests of fairly large scale frames.

The first omission is being covered by an experimental study of various relatively typical riveted and bolted connections now being conducted under Contract AF 33(616)-3780. It is expected that the work on this project will be concluded within a few months and that the information pertaining to the slow and rapid deformation behavior of column-base and beam-to-column connections will be made available as an AFSWC Technical Report.

As regards tests of large scale frames under slow and rapid loadings applied under laboratory conditions it is not believed that the value of the results produced in proportion to the funds expended would compare favorably with other research possibilities such as wider investigations of the behavior of the major structural elements under different force-time conditions.

IV. SUMMARY OF THE INVESTIGATION

1. Summary of the Investigation

1. A brief survey has been made of the literature pertaining to the static and dynamic behavior of mild steel structural frames and elements under conditions of slow and rapid loading.[2, 3, 7, 10, 11]

2. Experimental resistance-deflection-time information has been obtained from slow and rapid tests of beams and beam-columns deformed into the inelastic range.[1, 3, 5, 6, 7] In the slow tests, failures were produced in times of several minutes to a few hours, while the times involved in the rapid tests were on the order of tens of milliseconds.

3. A combined analytical and experimental investigation of the behavior of beams under oblique loading has been made.[3, 4]

4. A brief analytical and experimental study has been made of the effect of high shearing forces on the deflection of beams.[2]

5. The behavior of simple model frames when subjected to slow and rapid loadings has been investigated experimentally.[5, 8]

6. Analytical correlation studies based upon simple mathematical representations of material behavior have been made of several dynamic tests of beams and simple frames.[7, 9]

7. Relatively accurate analytical procedures for determining the inelastic deflection-resistance characteristics of redundant frame structures have been developed.[3, 8, 10]

8. The behavior of material obtained from a few rolled sections of structural steel has been determined experimentally under rapid loading.[11]

9. The behavior of several series of beams which were tested statically and one series which was tested dynamically to extensive inelastic deformations has been correlated fairly well with the known properties of the specimen materials as obtained under reasonably comparable conditions of stress, strain, and time.[3, 8, 11]

10. Rapid loading equipment capable of applying forces as large as ± 60,000 lb in times as short as 10 milliseconds to small structures and structural elements has been developed.[12]

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V. REVIEW OF THE INVESTIGATION

1. Survey of the Literature

In 1952 three publications[13, 14, 15] became available in which were summarized collectively the state of knowledge pertaining to "Steel Beams, Connections, Columns and Frames" under loading conditions ranging from "static" to transient "dynamic" rates. The availability of these reports made unnecessary an extensive survey of the literature concerning steel and steel frame structures, and, in addition, greatly simplified the finding of specific information useful in the advancement of the investigation being conducted at the University of Illinois. Of course, during the ensuing years, technical publications have been continuously monitored for pertinent information. Such references are listed in the various Technical Reports produced under Contract AF 33(616)-170. Abstracts of these reports form Appendix A.

2. General Nature of the Investigation

The investigation summarized in this report can be divided somewhat arbitrarily into three phases; (1) the development where necessary of analytical procedures and methods of computation which would be useful in the planning of test programs, interpretation of test results, and the general analysis of steel frame structures under slow and rapid loadings producing inelastic deformation; (2) the development of apparatus with which the required experiments could be performed; and (3) the experimental testing program. Each of these phases will be discussed in the following section.

3. Analytical Studies

The analytical phase of the project has included a study of the elementary theory of inelastic flexure of beams loaded laterally in the planes of major, minor and oblique axes; an investigation of various analytical expressions with which it might be possible to include the effects of various parameters believed to be important in the behavior of structures under rapid transient loading conditions producing extensive inelastic deformations; and the development of basic procedures useful in the analysis of indeterminate structures whose elements undergo inelastic deformation.

It was found in the first study[1, 2, 3, 4], through correlations with the experimental work, that the elementary theory of inelastic flexure when used with realistic stress-strain relationships including strain hardening permitted the computation of accurate resistance-deformation relationships for beams subjected to lateral loading applied slowly in the planes of the major, minor, or oblique axes provided that the beam section was of such geometrical proportions that the section was not made less effective by buckling effects.

The investigation pertaining to the development of analytical expressions including in parametric form the variables considered important in structural behavior formed the basis of a doctoral dissertation by Mr. F. L. Howland[7]. This procedure was used in the correlation studies presented in the Final Report for the period 1 September 1954 through 31 August 1955.

Mr. R. J. Mayerjak and Mr. A. Ang investigated possible methods for analyzing indeterminate frame structures when deformed inelastically. The procedure which resulted from these studies[8, 10] permits the determination of the resisting moments throughout the framework of an indeterminate structure for any inelastic deflection configuration. From these moments the loadings which could have produced them can be computed. While the procedure only determines resistance for an assumed deflection configuration, it is not limited to cases of "static" loading, since, with a suitable adjustment of the material properties to take into account increased resistance in accordance with known or expected straining rates at critical locations in the structure, it would be possible to analyze, proceeding step by step as regards time, the behavior of a structure subjected to dynamic loadings. In Reference No. 8 the material properties were adjusted (by increasing the yield stress 15 percent) to account for dynamic loading conditions. The solution of such a problem by this method would be tedious by hand computation, but it should be quite practicable by high speed digital computer.

4. Development of Testing Apparatus

In the early phases of the investigation, which were concerned with slow deformation tests of beams and beam-columns, the testing apparatus used was fabricated from the various loading frames and hydraulic jacking equipment available in the laboratory. However, with the incidence of dynamic testing, it became apparent that the drop weight equipment available would be inadequate for any experiments except those concerned with relatively small structural elements. Therefore, it was decided to develop rapid loading equipment with which it would be possible to apply forces as large as ± 60,000 lb in times as short as 10 to 15 milliseconds, maintain these loadings as long as desired, and then release them in times as short as 20 to 30 milliseconds. The successful development of this apparatus provided the laboratory staff with means of applying controlled loadings to structural elements of reasonable size.[12]

5. Experimental Investigations

The first of the experimental investigations were concerned with the behavior of beams and beam-columns made of I, wide flange, B, and M structural sections when subjected to slow lateral deformation in the plane of the major, minor, or 45° axis.[1, 2, 3, 4] Correlation of these experiments with the analytical studies indicated that the resistance of such structural elements can be computed with good accuracy if the actual stress-strain properties of the materials including strain hardening are used in conjunction with an elementary theory of inelastic flexure based upon assumed planar distribution of strain throughout a section. These methods yield results that are accurate even well into the range of strain hardening if the configuration of the specimen, its sectional properties, and restraint conditions are such that the primary mode of failure is not associated with lateral, local, or torsional buckling.

A closely related phase of the experimental investigation was concerned with beams and beam-columns which were tested with two types of rapid loading, pulses applied with a drop weight machine[3, 6, 7] and loadings which were applied in about 15 milliseconds to constant levels thereafter maintained by the special testing machine used.[11, 12]

In addition to the beam and beam-column tests, information concerning the behavior of frame structures was obtained from slow and rapid tests of small single bay bents whose elements were quarter scale models of 6 WF 25 sections.[3, 5, 8]

Throughout the project, the behavior of structural elements and model frames was correlated where possible with the properties of the materials from which they were made. Through 1955, the properties of the actual materials used could be determined only for the slow tests. The material behavior under rapid loading could only be estimated from information obtained by other investigators for similar steels. For the last series of beam and beam-column tests performed in 1956, both the slow and rapid loading properties were determined for material cut from the parent sections from which the beam and beam-column specimens were obtained.[11]

As was the case with the specimens tested slowly it was found that the resistances of beams and model frames tested rapidly were in good agreement with those determined on the basis of the known rapid stress-strain-time behavior of the materials involved.

Where local inelastic buckling was observed in a test series, it was less severe in the specimens tested rapidly than in those tested slowly. A partial explanation for this behavior may be obtained from consideration of the dynamic nature of the buckling process excluding time dependent effects in the material.[17] However, these effects as they pertain to the straining rate dependence of the general yielding resistance of mild steel may be the most important factor in these tests, since the greater the rate of center deflection of a beam with respect to the "flow" rate (rate of general yielding) at a given section, the more widespread along the length of the beam the yielding could be expected to be.

As was mentioned previously, the behavior of the structural elements which have been investigated experimentally has been related where possible to the static and dynamic properties of the materials from which the specimens were made. Therefore, the determination of material properties under both slowly and rapidly applied uniaxial stress has been an important phase of the project. This work has progressed concurrently with the beam and beam-column specimen tests, and within itself has yielded, in the case of the dynamic material studies, new information pertaining to the behavior of materials in rolled structural sections under conditions of rapid deformation.[11] A related phase of the beam and beam-column investigation was the determination of existing residual strains in the specimen parent sections as received from the mill, and also strains induced in the specimens as a result of fabrication by welding.[11]

In another phase of the program, the effect of shear on the inelastic behavior of wide flange beams subjected to static loading was investigated experimentally and analytically by W. J. Hall as the subject of his doctoral dissertation.[2] The beams tested were 8 WF 58 members which have sectional properties such that local buckling is not critical. A shear stress-strain curve was derived which can be used to estimate the component of deflection caused by general shear yielding. From the results of this study it was concluded that the effect of shear on the moment capacity of a wide flange beam is negligible for the usual range of structural practice, but that general shear yielding should be avoided since it leads to excessive deformation.

The several series of tests of beams, beam-columns, and model frames are summarized in the tables which are presented in Appendix B.

BIBLIOGRAPHY

1. Howland, F. L., "Static Load Deflection Tests of Beam-Columns," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 65, Contract AF 33(616)-170, Dec. 1953.

2. Hall, W. J., "Shear Deflection of Wide Flange Steel Beams in the Plastic Range," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 86, Contract AF 33(616)-170, Nov. 1954.

3. Howland, F. L., Egger, W., Mayerjak, R. J., and Munz, R. J., "Static and Dynamic Load Deflection Tests of Steel Structures," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 92, Contract AF 33(616)-170, Feb. 1955.

4. Egger, W., "Notes on the Analysis of Obliquely Loaded Beams in the Inelastic Range," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 98, Contract AF 33(616)-170, April 1955.

5. Wilkinson, C. L., and Howland, F. L., "The Response of Model Frames Subjected to Dynamic Lateral Loads," Univ. of Ill. Civil Engr. Studies, Struc. Res. Series No. 99, Contract AF 33(616)-170, June 1955.

6. Wojcieszak, R. F., and Howland, F. L., "The Response of Beam-Columns Subjected to Dynamic Lateral Loads," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 100, Contract AF 33(616)-170, June 1955.

7. Howland, F. L., "Inelastic Behavior of Mild Steel Beams Subjected to Transverse Impact," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 106, Contract AF 33(616)-170, August 1955.

8. Mayerjak, R. J., "A Study of the Resistance of Model Frames to Dynamic Lateral Load," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 108, Contract AF 33(616)-170, August 1955.

9. Howland, F. L., and Egger, W., "Correlations of Results of Dynamic Tests of Beams and Model Frames," Univ. of Ill. Civil Engr. Studies, Struct. Res. Series No. 109, Contract AF 33(616)-170, Sept. 1955.

10. Ang, A., and Massard, J. M., "A Method for the Analysis of Frames Subjected to Inelastic Deformation into the Range of Strain Hardening," Univ. of Ill. Dept. of Civil Engr., Tech. Rept. to the Air Force Special Weapons Center (AFSWC-TR-56-47), Contract AF 33(616)-170, Nov. 1956.

11. Wojcieszak, R. F., and Massard, J. M., "Slow and Rapid Lateral Loading Tests of Simply Supported Beams and Beam-Columns," Univ. of Ill. Dept. of Civil Engr., Tech. Rept. to the Air Force Special Weapons Center (AFSWC-TR-57-21), Contract AF 33(616)-170, Feb. 1957.

BIBLIOGRAPHY (Concluded)

12. Egger, W., "60-Kip Capacity Slow or Rapid Loading Apparatus," Univ. of Ill. Dept. of Civil Engr., Tech. Rept. to the Air Force Special Weapons Center (AFSWC-TR-57-22), Contract AF 33(616)-170, June 1957.

13. Hu, L. S., Byce, R. C., and Johnston, Bruce G., "Steel Beams, Connections, Columns and Frames," University of Michigan, Dept. of Civil Engr., Engineering Res. Institute Proj. M948, Report to Sandia Corporation, March 1952.

14. "Building in the Atomic Age," Proceedings of the Conference on, Massachusetts Institute of Technology, Dept. of Civil and Sanitary Engineering, June 16 and 17, 1952.

15. "Earthquake and Blast Effects on Structures," Proceedings of the Symposium on, Earthquake Engineering Research Institute and University of California, June 1952.

16. Clark, D. S., "The Behavior of Metals Under Dynamic Loading," Trans. ASM, Vol. 46, 1954, p. 34.

17. Hoff, N. J., "Buckling and Stability," J. Roy. Aero. Soc., Vol. 58, No. 1, (January 1954), p. 3.

APPENDIX A

ABSTRACTS OF TECHNICAL REPORTS PREPARED UNDER CONTRACT AF 33(616)-170

1. Static Load Deflection Tests of Beam-Columns

by

F. L. Howland

University of Illinois
Civil Engineering Studies
Structural Research Series No. 65
December 1953

This report is listed as the final report for the period of 1 July 1952 to 15 September 1953. The work described in this report included a series of static tests of beam-column specimens. These were lateral loadings of beam-columns under axial load with the lateral loading applied in both the strong and weak direction of resistance. In addition some information was included on the influence of axial loads on the response of beam-column specimens. The report also indicates that a brief analytical study had been made of the effect of oblique loading on beams.

A total of nine beam-column specimens were tested. These included two, 3 I sections, two, 4 M sections and five, 6 I sections. Actually only two of these specimens, one a 6 I and one a 4 M, were subjected to axial load in addition to lateral load. The results of the tests are summarized well in a series of three tables.

The effect of non-symmetrical bending including ideal plasticity, (that is, the case in which yielding occurs at a constant stress without strain hardening) is presented briefly. The results are presented in the form of an interaction diagram which relates the bending moments about the principal axes of a section as a function of the maximum fiber strain or the depth of yielding.

2. Shear Deflection of Wide Flange Steel Beams in the Plastic Range

by

W. J. Hall

University of Illinois
Civil Engineering Studies
Structural Research Series No. 86
November 1954

Methods of utilizing the reserve plastic strength of steel in structural design applications have merited considerable attention in recent years. Since deflections, rather than loads and stresses, often may be the controlling factors in such design, it is imperative that it be possible to calculate or at least make an estimate of the deflections under a specified loading in the plastic range. A review of the literature indicates that the discussions of the deflection of structures loaded beyond the elastic limit have been restricted to bending alone. Little theoretical or experimental information is available on the plastic deformation of structural beam sections in which high shear forces are present.

In order to study the deflection characteristics of beams subjected to high shear forces, two continuous beams of 8 WF 58 as-rolled section were tested. The main span of the beams was 9 ft and the overhangs used to maintain the end fixity of the latter span were 4 ft 5 in. long. The central load points were symmetrically spaced at the one-third points for the first beam and at the one-sixth points for the second beam. Each beam thus had sections subjected to pure bending, bending combined with low shear, and bending combined with high shear. Loads, strains, and deflections were measured, and pictures of the whitewashed portions were taken to record the yield patterns. In order to made the pertinent data available to other investigators, the load, shear, moment, and deflection data at key points are tabulated in the report. The detailed results of the tests are presented in tables and figures. In analyzing the data it was assumed that the deflections due to bending and shear could be separated and that their combined effect could be obtained by superposition. From the shear versus shear strain data, a shear stress-strain curve was derived which can be used to estimate the component of deflection caused by shear when regions of the beam have undergone general shear yielding. As far as is known from the literature, these tests represent the first large-scale tests of continuous beams loaded far into the plastic range in which extremely high shear forces are present. On the basis of these tests it is concluded that no measurable reduction in the moment capacity (for the section and span used) was indicated.

The importance of the shear aspect and its effect on the behavior of beams is evaluated briefly. Theoretical examples are presented which illustrate the effects of general shear yielding of the web on the deformation characteristics of beams. This could be of major importance when shear yielding of the web occurs.

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A paper of the same title by W. J. Hall and N. M. Newmark has been published as Proceedings Separate Vol. 81, No. 814 of the American Society of Civil Engineers and a somewhat more condensed version will appear in the 1957 ASCE Transactions. The Proceedings paper is a condensed summary of the data presented in the above report but in addition compares some of the test results with current design specifications. Portions of the test results indicate that where large shear forces are present the factors of safety may be somewhat low. This would seem to be particularly true for loadings of the type used in these tests. Since general shear yielding in the web can cause excessive deflections, the recommended practice is to avoid high shear when possible.

3. Static and Dynamic Load Deflection Tests of Steel Structures

by

F. L. Howland, W. Egger, R. J. Mayerjak, and R. J. Munz

University of Illinois
Civil Engineering Studies
Structural Research Series No. 92
November 1954

Part one of this report presents a survey of the literature pertaining to elasto-plastic and inelastic behavior of structures.

Part two describes static tests to failure of steel beam columns, an analytical study of the effect of axial loads on the response of wide flange beams, and the description of specimens, test apparatus, instrumentation, and results pertaining to the beam-column study.

The third part is a description of model studies of frames subjected to static lateral loads along with the description of the specimens, the apparatus, the analysis used and the results of the tests.

In part four the static oblique loading of steel beam columns is described including the analytical investigation, the experimental investigation and the summary of results.

In part five the dynamic response of beams is discussed including a criterion for determining the dynamic yield stress and description of a dynamic test in a drop testing machine of one 3 I specimen including instrumentation procedure, results and conclusions.

The conclusions listed in this report state that this program has indicated that the static response of steel frames and frame elements can be predicted with a theory that is similar to the elasto-plastic theory but which includes the effect of strain hardening of the material. However, the tests have also indicated that the mode of failure can cause significant deviations from the predicted response even though strain hardening has been included. For nearly all of the tests the experimentally determined capacity was between that predicted by the elasto-plastic theory as a lower bound and that predicted by a theory that includes strain hardening as an upper bound. In the weak direction of loading, although failures generally occurred by local buckling and the load capacity was restricted, the response nevertheless approached the upper bound. In the strong direction tests, however, the failures by lateral buckling cause significant deviations from the upper bound predictions and, in many cases, the elasto-plastic theory, which neglects strain hardening, provided the best predictions. However, the deviation depends on many factors such as the restraint conditions which are not incorporated in the theories at this time.

In the application of these theories to the prediction of response, the effect of axial load must be included. In the weak direction tests, the thrust had only a small effect on the moment curvature relationship and had to be included only in the computation of the applied moments. In the strong direction tests, the thrust had to be included in the computations of the bending moments and of the curvatures corresponding to these moments.

The dynamic tests of the beam specimens have indicated that the resistance to dynamic loads differs significantly from the static resistance. The change in resistance noted occurs because of an increase in the yield stress of the material. This increase is, at first, a result of the delay yield phenomenon which extends the elastic range of the response. After yielding occurs the resistance decays to a level that is greater than the static resistance. The results of dynamic tests that were reported are of a preliminary nature and continued investigation[5, 6, 7, 8, 9, 11] has produced a better understanding of the dynamic behavior of steel structures.

4. Notes on the Analysis of Obliquely Loaded Beams in the Inelastic Range

by

W. Egger

University of Illinois
Civil Engineering Studies
Structural Research Series No. 98
April 1955

The previous investigation* of the static load capacity and response of obliquely loaded beams in the inelastic range was restricted to a small range of deflections by limiting the maximum magnitude of the strains to the so-called "flat" portion of the stress-strain relationship. This restriction excluded the influence of the strain-hardening of the material on the load-capacity of the beam. The elasto-plastic theory described in the report, though describing the behavior of the structure reasonably well, was not suitable for a practical solution of the oblique loading problem.

In order to overcome the limitation of the elasto-plastic theory on the strain magnitude, the theoretical solution has been extended to include the influence of strain-hardening of the material on the load capacity so that the response can be predicted up to deflections of approximately 20 times the elastic limit displacement. It was found that the contribution of the strain-hardening to the load-capacity could be obtained directly from the previous elasto-plastic analysis so that a minimum of additional computation is required to extend the range of applicability of the theory.

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* Howland, F. L., Egger, W., Mayerjak, R. J., and Munz, R. J., "Static and Dynamic Load-Deflection Tests of Steel Structures" Civil Engineering Studies, Structural Research Series No. 92, University of Illinois, 1955.

By means of the extended theoretical solution it was possible to evaluate the applicability of the rigid-plastic analysis method by comparing the response and load-carrying capacity of a cantilever beam for various directions of load application. This comparison has indicated that the rigid-plastic analysis can be used to predict the deflection path with sufficient accuracy except for the cases in which the load is applied at a small angle to the web or Y-axis of the section. Major differences between the results of the theories occur in the predicted load-capacity since the limiting capacity of the rigid-plastic theory is the "fully-plastic" resistance for the structure which neglects the contribution of the strain-hardening of the material to the load-capacity.

5. The Response of Model Frames Subjected to Dynamic Lateral Loads

by

C. L. Wilkinson, and F. L. Howland

University of Illinois
Civil Engineering Studies
Structural Research Series No. 99
June 1955

The principal objective of this investigation was to determine the inelastic resistance of model frames subjected to dynamic lateral loads. In this study, the observed dynamic resistance of the model frames is compared with the "theoretical" and observed static resistance. This comparison aids the evaluation of the parameters which determine the static and the dynamic resistance. A study was made of assumed forms of the dynamic resistance of the frames on the basis of the relationship between the energy inputs and the maximum deflections. This was a simple and convenient procedure from which many of the trends of the dynamic resistances could be determined.

Four model frames specimens were tested by subjecting each specimen to a dynamic lateral load applied along the axis of the top girder. The specimens were essentially ideal frames with fixed-column bases and column sections which were one-quarter scale models of a 6WF25 section. The applied load, accelerations, deflections, and maximum fiber strains were recorded as functions of time during each test.

The dynamic resistance of each specimen was computed from the observed loads, accelerations, and deflections by means of a single-degree-of-freedom system analysis. The dynamic resistance curves of all frames had an elastic slope less than the theoretical static resistance, but approximately the same as the observed static resistance. The dynamic resistance was greater than the static resistances when general yielding occurred and retained this increase until a deflection of from 8 to 11 times the theoretical static elastic limit deflection was obtained. After this deflection had been reached, the dynamic resistances closely approached the theoretical static resistance for the remainder of the test. The increase in the observed dynamic resistance over the theoretical static resistance has been predicted reasonably well by consideration of the strain rates in the frame.

Conclusions. The dynamic resistance of the frames tested in this investigation was found to be higher at yielding than the static yield resistance. After yielding occurred, the inelastic resistance approached the theoretical static response and in the later stages of loading the dynamic resistance can be considered to be the same as the theoretical static resistance. For large deflections, the theoretical static curves are a good approximation for the dynamic resistance since the increase in dynamic resistance at yielding contributed only a small amount to the total energy. The dynamic resistance was found to be significantly higher than the observed static resistance since the local buckling and twisting of the columns, which reduced the capacity of the frame in the static tests, did not have time to occur during the dynamic tests.

Although these tests do not provide enough information to permit determination of the response of any frame, they do give a general picture of the response of frames and show what can be expected under conditions used in these tests.

6. The Response of Beam-Columns Subjected to Dynamic Lateral Loads

by

R. F. Wojcieszak

University of Illinois
Civil Engineering Studies
Structural Research Series No. 100
June 1955

The investigation of the response of dynamically loaded beam-columns consisted of testing in a drop test machine four pin-ended beams with an effective span of 80 in. The beams were fabricated from 4 M 13.0 rolled sections which were normalized to obtain uniform material properties. One pair of the specimens was tested in the strong direction while the other pair was tested with the section oriented in the weak direction with respect to the applied lateral load. One specimen in each pair was subjected to a constant axial load in addition to the dynamic lateral load.

A test consisted of dropping the 500-lb weight of the drop test machine from several heights to vary the energy input. In each test the lateral load, deflected shape of the beam, strains, and axial load, if present, were recorded as functions of time.

The test results indicate that increasing the energy input increases the duration and amplitude of the load, and the maximum deflection. In general, the axial load did not appreciably affect the resistance to lateral deformation of the beam-columns oriented in the strong direction when the center deflection was small, approximately less than three times the static yield deflection. For larger deflections the axial load had the effect of causing the response to decay toward the theoretical static response curve and the resistance of the specimen was often considerably less than the resistance of the specimen without axial load. With the weak direction specimens, as was expected, the resistance-deflection relationship was affected more by the axial load than was the case in the tests of the specimens with the section oriented in the strong direction.

The correlation of the dynamic resistance to lateral deformation with the theoretical static resistance was obtained by comparing the actual energy-input and maximum deflections with the strain energy predicted from the theoretical static resistance-deflection relationship at the same deflection. When the energy input at the maximum deflection was greater than the corresponding strain energy predicted using the theoretical static resistance, the yield stress used for the static resistance deflection relationship was increased until the strain energy approximately equaled the energy input measured in the test.

By comparing the energy-maximum deflection relationships obtained from these tests, it was found that higher values of the yield stress were required as the energy input increased. It was also found that the axial load had little effect on the resistance in the deflection range from approximately zero to three times the static yield deflection. However, for larger deflections the axial load caused the resistance to decrease with increasing deflections in the same manner as was noted in the static tests of beam-columns. In the case of the weak direction specimens the increase in yield stress with increased energy-input was smaller than noted in the strong direction tests.

7. Inelastic Behavior of Mild Steel Beams Subjected to Transverse Impact

by

F. L. Howland

University of Illinois
Civil Engineering Studies
Structural Research Series No. 106
August 1955

The response and resistance of a dynamically loaded mild steel beam has been approximated using a single-degree-of-freedom model. The resistance of the beam and model has been considered to consist of the following phases: (1) an initial elastic resistance; (2) a subsequent inelastic resistance which may be a function of the displacement, velocity, and time; and (3) finally, a recovery resistance that is essentially elastic. The elastic phases of the resistance are functions of the displacement only and have not been considered in this investigation.

The initial phase of the inelastic resistance of the model was found to be a function of the velocity, the time, and the static elasto-plastic resistance. This time-dependent resistance has been assumed to be given by the following expression:

$$\mathring{w} = (1/K)\mathring{R} + \alpha[R - R_{fp}]$$

where $\mathring{w}$ and $\mathring{R}$ are the rate of change of the displacement and resistance, respectively, with respect to time; K is the elastic spring constant; R is the resistance; and R_{fp} is the static "fully-plastic" resistance. The time-dependent resisting function is applicable until the time when it is equal to or less than the static resistance, which includes the effect of strain-hardening of the material.

From the information in the literature, and from a consideration of the static inelastic deformation process, it was found that the parameter α could be expressed as follows:

$$\alpha \, K \, T = (\beta T/C)^{n} \, (u')^{1-n}$$

where u' is a dimensionless velocity, T is the period of the beam, and β, C, and n are constants. The constant β, which is determined by the load distribution along the beam, relates the velocity u' to the maximum strain-rate. Because of the derived form of β, the time-dependent resisting function is restricted to statically determinate beams. The constant C is essentially a dynamic shape factor. Both C and n are determined, in part, by the relationship between the lower yield stress of the material and the strain-rate.

The applicability of the procedure was investigated by predicting the response of several beams and frames for known loads and comparing the predicted response with the response measured in tests. This comparison has indicated that the magnitude of the derived constants are essentially correct but that further adjustment of the constant β is necessary.

From a brief study of the time-dependent resistance, an approximate method has been outlined for estimating a dynamic "fully-plastic" resistance to replace the more complex time-dependent resistance.

Two additional investigations are included as Appendices: (1) A criterion for estimating the dynamic elastic limit resistance and displacement of the structure. This criterion is based on the available information

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concerning the delay time for yielding. (2) A semigraphical procedure for including the effect of strain-hardening of the material on the static resistance and response of inelastically deformed structures.

Summary. From this investigation of the inelastic resistance of mild steel beams subjected to transverse impact it has been found that: 1. in the early stages of the inelastic response, the resistance of mild steel beams exhibits a definite time dependent character; 2. when the displacement of the beam becomes sufficiently large, the resistance of the structure is the static load deflection relationship for the beam if strain hardening of the material is included in the static analysis; 3. if an inelastic resisting function for the beam is assumed, the parameters required in the function can be derived from the information available from the literature and by considering the static elasto-plastic behavior of the structure; 4. from a study of the inelastic resistance during time dependent resistance portion of the response, an approximate procedure for estimating the dynamic fully plastic resistance can be developed.

8. A Study of the Resistance of Model Frames
to Dynamic Lateral Load

by

R. J. Mayerjak

University of Illinois
Civil Engineering Studies
Structural Research Series No. 108
August 1955

The resistance of model steel frames subjected to dynamically applied lateral loads which produce large deflections (nearly 30 times the elastic limit deflection) is studied. The results of static and dynamic tests are presented. These provide a basis for the comparison of the dynamic with the static resistance of model frames.

The models used in these tests were made from ASTM A-7 steel and were machined to be approximately 1/4 scale replicas of a standard 6 WF 25 section. In all of the tests the sections were tested in their strong direction of resistance. There were two center loaded simple beam tests, one third point loaded simple beam test, four rigid top girder frame tests, and six flexible top girder frame tests. In two of the flexible top girder frame tests, axial loads were applied to the columns of the frames in addition to the lateral load. The rigid top girder frames were square bents approximately 15 in. by 15 in. The flexible top girder frames were rectangular bents approximately 16.5 in. high and 30 in. long.

The experimentally determined resistance functions for the frames tested in this investigation are in good agreement with those theoretically predicted. It was found that the characteristics of the resistance function for dynamic loading conditions can be explained and predicted by taking into account the dynamic stress-strain properties determined from investigations of tensile coupons of a similar material.

Relationships for estimating the resistance function of full sized structures subjected to dynamically applied loads are developed. The procedures are based on dimensionless relationships which enable one to determine the angle change in a member subjected to large inelastic deformations. When this is done, the load-deflection analysis can be made by conventional procedures.

9. Correlations of Results of Dynamic Tests of Beams and Model Frames

by

F. L. Howland and W. Egger

University of Illinois
Civil Engineering Studies
Structural Research Series No. 109
September 1955

The object of this program is to determine the effects of blast on buildings and structures by investigating the load capacity of steel structures and elements under both static and dynamic conditions. For a static load the load capacity can be obtained in the form of load-deflection and moment-curvature relationships for the structure. When the structure is loaded dynamically, the resistance or load capacity no longer is a function only of the deflection but can depend also on the strain rate and possibly the time. Thus, a second objective of the program is the correlation of the dynamic and the static resistances.

Previously the emphasis of the program has been concentrated on investigations of the static resistance of steel structures. The results of these investigations have been summarized in the report which is the final report of the program for the period 15 September 1953 to 1 September 1954.[3] These studies have indicated that the static resistance or load-deflection relationship can be obtained by means of the available theory of plasticity if the influence of strain hardening of the material is included in the analysis and if the structure does not develop a lateral or local failure during the loading process. A limited study of two aspects of the static response problem has been included in the present contract and the results of these studies have been distributed as technical reports. The first of these investigations is concerned with the influence of strain hardening of the material on the response and resistance of obliquely loaded steel beams. The second investigation was a study of the effect of combined bending and shear on the resistance and deflection of steel wide flange beams. Abstracts of these reports are included in the appendix.

The major emphasis during the present contract has been placed on the investigation of the dynamic resistance of mild steel structures. The determination of the dynamic resistance and the correlation of the dynamic and static resistances for various structures have been studied by both experimental and analytical methods. In the experimental studies, several types of specimens have been tested under a variety of loading conditions. The results of the various experimental investigations have been reported in references 5 through 8. Abstracts of the contents of these reports are included in the appendix. The information obtained from the various experimental investigations has been used: 1. to determine the dynamic resistances for the structures; 2. to determine the variations in the form of the dynamic resistance; and 3. to provide experimental data for use in checking the applicability and validity of the methods of analysis that have been developed.

From the results of the tests it has been found that the dynamic resistance of a structural element can differ appreciably from the static resistance.

The dynamic behaviors of test structures were analyzed by assuming that the actual test structures could be approximated as single-degree-of-freedom systems. However, slightly different approximations to the form of the dynamic resistances of the structures were made by the two principal investigators, Howland and Mayerjak.

Howland assumed that the resistance of the structure was of an elasto-plastic nature similar to the resistance of mild steel to uniform axial deformation if the upper and delayed yield effects are neglected but dependence of the instantaneous resistance stress upon the rate of general yielding is retained. After general yielding is completed and strain hardening begins, it is assumed that the dynamic resistance is the same as the static resistance. In the formulation of the resisting function, parameters were included to take into account the distribution of load, the boundary conditions, the shape of the cross section of the structural element, and the material from which it was made.

Mayerjak based his computations on the stress-strain relationship for the material rather than the overall resistance of the structure. The dynamic increase in resistance was taken into account by increasing the stress level of general yielding in accordance with the average strain rates expected. This procedure is fairly accurate since the relation between the stress level and the rate of general yielding for mild steel is relatively insensitive to changes of strain rate no greater than one order of magnitude, a range which includes the average strain rates encountered in the tests.

Using the dynamic stress-strain relationship, Mayerjak computed dynamic resistance deflection relationships for his frames by the same general method used in obtaining the static load-deflection curves if inertia effects are neglected. This procedure is not restricted to statically determinant systems or those which can be approximated by single-degree-of-freedom analogs.

Howland later modified his procedure to a simpler approximate method in which the general form of the dynamic resistance function for the structure is the same as that for static loading except for an increase in the level of the fully plastic resistance. This level is determined by a consideration of the elastic response of the structure as compared to the dynamic resistance computed using the velocity dependent relationship of Howland's first method. The approximate method was used to compute values for the dynamic fully plastic resistances of the specimens as they were tested with their various loadings. These results are compared with the values of fully plastic resistance obtained by tests in which the data are interpreted on the basis of the single-degree-of-freedom analog.

Conclusions. Comparisons of the specimen resistances obtained experimentally with those computed using the approximate method indicate that: 1. The ratio of the dynamic fully plastic resistance to the static fully plastic resistance is not changed appreciably by the changing of the orientation of the cross section, span of the beam, or shape of the cross section. (This indicates that the increased resistance is a function of the specimen material and not the conformation of the specimen.) 2. For the tests considered, the dynamic fully plastic resistance can be related to the static lower yield stress of the material. (This indicates that the actual critical strain rates occurring in the test structures were of the same order of magnitude or else that the material is relatively insensitive to changes in strain rate.) 3. The addition of a constant axial load did not change the total internal resistance of the structure appreciably from the value it would have had if no thrust were present.

Major differences in the form of the dynamic resistance deflection relationship were noted when the resistance of the determinant and the indeterminant structures were compared.

10. A Method for the Analysis of Frames Subjected to Inelastic Deformation into the Range of Strain Hardening

by

A. Ang and J. M. Massard

University of Illinois, Department of Civil Engineering
Technical Report to
The Air Force Special Weapons Center (AFSWC-TR-56-47)
November 1956

A method for determining the resistance of frame structures composed of elements having individual resistance-deformation characteristics of any monotonically increasing form that can be described graphically is presented. The resisting moments in a structure which correspond to a given set of displacements of the loaded joints are found by a trial and error procedure made convenient by use of moment-end slope relationships for the individual members. After the resisting moments have been obtained, the corresponding set of loads required to produce the particular joint displacements are computed.

By solving a set of such problems, load-joint displacement relationships can be obtained for a range of loads, or conversely for a range of displacements.

The general nature of the method is such that it is perhaps most useful in research applications.

A simplified procedure for the analysis of independent frames using moment distribution with bilinear approximations to the moment-end slope relationships is presented in the appendix.

The procedure used in this report involves assuming displacements of the loaded joints (the general deflected shape of the structure), and obtaining the resistance of the structure to that particular deformation pattern assuming that a reversal of strain does not occur any place in the structure. The practicability of the method depends upon a convenient means of relating the resistance of a member to its deflected shape. In this method, the resisting moments at the ends of a member are related by graphical representation to the end slopes of the member. Using these relationships (which apply to any wide flange section within the limits of error given below) resisting moments can be found for the assumed deflected shape of the frame structure using an iterative trial and error procedure. After the resisting moments have been found, the combination of loads that could produce the assumed deflection configuration of the structure can be computed. The moment curvature relationships presented in this report can be used with an error of less than ± 3 % in the resisting moments for all structural wide flange sections.

Neither of the methods presented in this report takes into account the effect of non-rigid connections on the behavior of the frame considered. It is expected that the procedures will be extended to include this effect as a part of the work in the Contract AF 33(616)-3780.

11. Slow and Rapid Lateral Loading Tests of Simply Supported Beams and Beam-Columns

by

R. F. Wojcieszak and J. M. Massard

University of Illinois, Department of Civil Engineering

Technical Report to
The Air Force Special Weapons Center (AFSWC-TR-57-21)
February 1957

The two major purposes of the program described in this report were to determine experimentally the resistance of beam and beam-column specimens to inelastic deformations applied slowly and rapidly; and, if possible, to correlate these resistances with the static and dynamic properties of the material from which the specimens were made.

The results obtained indicate that, beyond the static elastic limit, the resistance of a mild steel beam or beam-column to a lateral displacement produced rapidly is greater than that corresponding to the same lateral displacement produced slowly; and that the increase in the resistance of the beam with the rapidity of the lateral deformation can be explained with an experimental error in the limited range of strain in which comparisons were possible, by consideration of experimentally determined dynamic properties of the specimen material which included delayed yielding and rate of general yielding behaviors typical of mild steel.

The experimental work described in the report includes the determination of the mechanical properties in the specimen materials, the determination of the residual strains in the beam specimens, the beam and beam-column investigation which included a total of nine individual specimen tests and a correlation of the beam resistance with the material properties.

Conclusions. a. Beyond the static elastic limit, the resistance of a mild steel beam or beam-column to a lateral displacement produced rapidly is greater than corresponding to the same lateral displacement produced slowly. b. The increase in the resistance of a beam with the rapidity of the lateral deformation can be explained, within the limits of measured strain and experimental error, by consideration of the delayed yielding and rate of general yielding behavior of the specimen material corresponding to stress-strain-time conditions comparable to those produced in the beam. c. When under a constant axial load, the resistance of a beam-column specimen to a rapidly or slowly applied lateral deformation is less than that of a similar beam without axial load. d. A beam which is tested slowly with increments of displacement will have a resistance at any inelastic displacement less than that exhibited by a beam loaded slowly but continuously. e. The delayed yielding and rate of general yielding behavior determined experimentally from the coupons which were cut from the structural sections tested were comparable to those that had been obtained at the University of Illinois and elsewhere for mild steel.

Time did not permit a correlation of the slow and rapid loading behavior of the beam-column specimens with the properties of materials from which they were made as was done for the beam specimens. However, the authors believe that, as in the case with the beam specimens, the difference in slow and rapid loading behavior could be explained in terms of the stress-strain-time properties of the specimen materials.

Even though the scope of the investigation, at least as regards the beam and beam-column tests described in this report, is rather limited, it is believed that some procedure of determining the dynamic resistance of a structural element from considerations of the dynamic properties of the material from which it is made is generally applicable to problems of determining the response of steel frame structures to conditions of loading or deforming that vary in time from slow or static conditions to those in the range which structures of this type might be expected to resist under atomic bomb attack or earthquake shock.

12. 60-Kip Capacity Slow or Rapid Loading Apparatus

by

W. Egger

University of Illinois, Department of Civil Engineering
Technical Report to
The Air Force Special Weapons Center (AFSWC-TR-57-22)
May 1957

In this report is described the design, construction and operational characteristics of the 60-kip slow and rapid loading units developed at the University of Illinois under Contract AF 33(616)-170. The desired operational characteristics of the units as described in the contract covering their construction were largely met by the units as completed. These were: that it be possible to apply a loading either slowly or rapidly of a magnitude of ± 50 kips; that the units have maximum stroke of 18 inches; that it be possible to apply the maximum load in a time on the order of and if possible less than 10 milliseconds; and that it be possible to release the load in a controlled time of approximately 30 milliseconds. In the report the actual load versus time relationships obtained through the use of these units are compared with load time relationships which were obtained from thermodynamic considerations of the mass rate of flow of the gases involved. In the region in which the theoretical relationships are applicable the agreement is quite good.

APPENDIX B

TABULATION OF TESTS PERFORMED UNDER CONTRACT

AF 33(616)-170

Note:

The values presented in the Tables were obtained directly from information given in the report listed as the reference. In some cases where the same test information was used in more than one report minor discrepancies may be evident.

TABLE OF NOTATION FOR APPENDIX B

Notation

The following notation has been used in this appendix:

NA = Not Applicable

NR = Not Reported

P_m = Maximum Applied Lateral Load

P_e = Applied Lateral Load which Would Initiate Inelastic Behavior with No Axial Thrust

Q_m = Maximum Lateral Load Resistance

Q_e = Elastic Limit Resistance

T_m = Applied Axial Thrust

T_e = Axial Thrust which Would Stress the Entire Cross Section to Yield

x_m = Maximum Center of Span Deflection

x_e = Center of Span Deflection Corresponding to Yield

xx = Strong Direction Orientation

yy = Weak Direction Orientation

Loading:

A = Axial

L = Lateral

Loading Device:

C = 120^k Baldwin Machine

3M = 3000^k Machine

HJ = Hydraulic Jack

PJ = Pneumatic Jack

S = Springs

W = 500-lb Drop Weight

20^k = 20^k Slow or Rapid Machine

60^k = 60^k Slow or Rapid Machine

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured: Axial Thrust T_m/T_s	Phenomena Measured: Load Point Accel., g's	Phenomena Measured: Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
60S 3I7.5	1	3I7.5		136	x-x	Incremental Deflection	Many Hours	L-HJ	None	1.29	0	NA	9.82	1.29	7	0
20S 3I7.5	1	3I7.5	"	40	x-x	"	"	"	"	2.21	0	NA	27.0	2.21	7	0
60S 6I12.5	1	6I12.5	"	136	x-x	"	"	"	"	1.34	0	NA	10.3	1.34	9	0
20S 6I12.5	1	"	"	40	x-x	"	"	"	"	1.99	0	NA	29.4	1.99	9	0
42S 6I12.5	1	"		88	x-x	"	"	L-HJ A-HJ	Constant 10.6 ksi	1.59	0.26	NA	8.13	1.59	9	0
6YOS 6I12.5	1	"		136	y-y	"	"	L-HJ	None	1.82	0	NA	10.4	1.82	8	0
2YOS 6I12.5	1	"	"	40	y-y	"	"	"	"	2.51	0	NA	22.9	2.51	8	0
40S 4M13.0	1	4M13.0	"	88	x-x	"	"	"	"	1.64	0	NA	7.02	1.64	9	0
415S 4M13.0	1	"		88	x-x	"	"	L-HJ A-HJ	Constant 16.6 ksi	1.35	0.32	NA	5.89	1.35	9	0
B-1	2	8WF58		NA	x-x	Incremental Deflection	Many Hours	L-3M L-HJ	None	1.90 (1)	0	NA	22.8	NR	9	0
B-2a	2	"		NA	x-x	"	"	L-3M L-HJ	"	3.06 (1)	0	NA	102	NR	9	0
B-2b	2	"		NA	x-x	"	"	L-3M	"	≅1.38	0	NA	18.1	NR		0

*References are listed at end of text

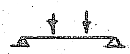
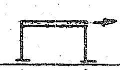
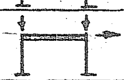
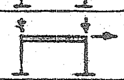
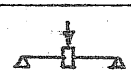
(1) P_e based on beginning of general shear yielding.

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Time to Max. Lateral Load, Seconds	Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Axial Thrust T_m/T_e	Load Point Accel., g's	Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Fast
40S 4M13.0	3	4M13.0		88	x-x	Incremental Deflection	Many Hours	L-HJ	None	1.46	0	NA	7.11	1.46	9	0
41S 4M13.0	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 17.3 ksi	1.35	0.30	NA	5.89	1.35	9	0
4Y0S 4M13.0	3	"	"	88	y-y	"	"	L-HJ	None	1.88	0	NA	12.1	1.88	9	0
4Y1S 4M13.0	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 14.8 ksi	1.78	0.32	NA	6.81	1.78	9	0
60S 6I12.5	3	6I12.5	"	136	x-x	"	"	L-HJ	None	1.33	0	NA	10.4	1.33	9	0
41S 6I12.5	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 10.9 ksi	1.59	0.24	NA	8.13	1.59	9	0
6Y0S 6I12.5	3	"	"	136	y-y	"	"	L-HJ	None	1.79	0	NA	7.78	1.79	8	0
4Y1S 6I12.5	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 7.6 ksi	1.57	0.16	NA	5.34	1.57	9	0
40S 6B15.5	3	6B15.5	"	88	x-x	"	"	L-HJ	None	1.34	0	NA	10.2	1.34	9	0
41S 6B15.5	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 13.5 ksi	1.19	0.36	NA	11.9	1.19	9	0
4Y0S 6B15.5	3	"	"	88	y-y	"	"	L-HJ	None	1.78	0	NA	29.8	1.78	9	0
4Y1S 6B15.5	3	"	→ " ←	88	"	"	"	L-HJ A-HJ	Constant 9.0 ksi	1.37	0.22	NA	13.1	1.37	6	0

*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured: Axial Thrust T_m/T_e	Phenomena Measured: Load Point Accel., g's	Phenomena Measured: Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
Frame Beam 1	3	1/4 scl 6WF25		NA	y-y	Incremental Deflection	Hours	L-C	None	1.8	0	NA	NR	1.8	2	0
Frame Beam 7	3	"	"	NA	x-x	"	"	L-C	"	1.4	0	NA	NR	1.4	2	0
Frame Beam 4	3	"		15	y-y	"	"	L-C	"	3.1	0	NA	100	3.1	2	0
Frame Beam 6	3	"	"	15	x-x	"	"	L-C	"	2.1	0	NA	70	2.1	2	0
Frame 1	3	1/4 scl 6WF25		15	y-y	Incremental Deflection	Hours	L-HJ	None	3.3	0	NA	140	3.3	4	0
Frame 2	3	"		15	y-y	"	"	L-HJ A-S	Constant 8.89 ksi	1.7	0.25	NA	75	1.7	4	0
Frame 3	3	"		15	x-x	"	"	L-HJ	None	1.75	0	NA	90	1.75	4	0
Frame 4	3	"		15	x-x	"	"	L-HJ A-S	Constant 8.73 ksi	1.45	0.23	NA	90	1.45	4	0
4XYOS 6B	3	6B15.5		87	45°	Incremental Deflection	Many Hours	L-HJ	None	2.36	0	NA	39	2.36	13	0
4XY1S 6B	3	6B15.5		87	45°	"	"	L-HJ A-HJ	Constant 10 ksi	1.64	0.25	NA	23	1.64	13	0

*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured (Maximum values listed): Axial Thrust T_m/T_e	Phenomena Measured (Maximum values listed): Load Point Accel., g's	Phenomena Measured (Maximum values listed): Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
46D 3I 7.5-1	3	317.5		80	x-x	Drop Weight 500 lb 3 in.	0.035	L-W	None	0.98	0	NR	1.33	NR	3	0
" " 2	3	"	"	"	"	500 lb 3 in.	0.035	"	"	0.98	0	NR	1.33	NR	3	0
" " 3	3	"	"	"	"	500 lb 6 in.	0.035	"	"	1.52	0	NR	2.02	NR	3	0
" " 4	3	"	"	"	"	500 lb 6 in.	0.035	"	"	1.52	0	NR	2.02	NR	3	0
" " 5	3	"	"	"	"	500 lb 12 in	0.030	"	"	1.80	0	NR	3.05	NR	3	0
" " 6	3	"	"	"	"	500 lb 12 in	0.030	"	"	1.80	0	NR	3.05	NR	3	0
" " 7	3	"	"	"	"	Calibration	NR	NR	"	NR	0	NR	NR	NR	3	0
" " 8	3	"	"	"	"	500 lb 24 in	0.010	L-W	"	2.58	0	NR	4.85	NR	3	0
" " 9	3	"	"	"	"	500 lb 30 in	0.013	"	"	2.08	0	NR	6.23	NR	3	0

*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured: Axial Thrust T_m/T_e	Phenomena Measured: Load Point Accel., g's	Phenomena Measured: Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
Frame 3	5	1/4 scl 6WF25		15	x-x	Incremental Deflection	Hours	L-HJ	None	1.75	0		90	1.75	4	0
Frame 6	5	"	"	"	"	Loaded Rapidly	0.007	L-20k	"	1.68	0	80	13.3	1.66	4	0
7	5	"	"	"	"	"	0.006	"	"	1.83	0	75	19.3	1.78	4	0
8.1	5	"	"	"	"	"	0.006	"	"	2.13	0	95	25.2	1.93	4	0
8.2	5	"	"	"	"	"	0.006	"	"	2.81	0	170	26.0	2.20	4	0
9	5	"	"	"	"	"	0.006	"	"	2.77	0	120	50.4	2.06	4	0

*References are listed at end of text

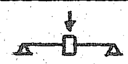
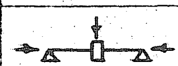
SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured: Axial Thrust T_m/T_e	Phenomena Measured: Load Point Accel., g's	Phenomena Measured: Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
40XD 4M-1	6	4M13.0		80	x-x	Drop Weight 500 lb 12 in	0.024	L-W	None	1.25	0	NR	1.62	NR	8	0
2	6	"	"	"	"	500 lb 24 in	0.022	"	"	1.64	0	NR	2.75	NR	8	0
3	6	"	"	"	"	500 lb 48 in	0.007	"	"	1.93	0	NR	5.63	NR	8	0
4	6	"	"	"	"	500 lb 72 in	0.007	"	"	2.82	0	NR	10.3	NR	8	0
41XD 4M-1	6	"		"	"	500 lb 12 in	0.024	L-W A-S	Constant 8.93 ksi	1.23	0.24	NR	1.68	NR	8	0
2	6	"	"	"	"	500 lb 24 in	0.022	" "	Constant 8.72 ksi	1.49	0.24	NR	2.[illegible]1	NR	8	0
3	6	"	"	"	"	500 lb 48 in	0.007	" "	Constant 7.74 ksi	1.83	0.21	NR	7.00	NR	8	0
4	6	"	"	"	"	500 lb 72 in	0.007	" "	Constant 6.24 ksi	2.82	0.17	NR	13.8	NR	8	0

*References are listed at end of text

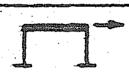
Metz Reference Room
Civil Engineering Department
B106 C.E. Building
University of Illinois
Urbana, Illinois 61801

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated)			Axial Thrust	Phenomena Measured (Maximum values listed)				Computed Lat. Ld. Resistance, Q_M/Q_e	Material Coupons Tested	
						Type of Loading or Deforming	Time to Max. Lateral Load, Seconds	Testing Machine Used	Type of Axial Thrust	Lateral Load P_M/P_e	Axial Thrust T_M/T_e	Load Point Accel., g's	Deflections x_M/x_e Ld. Pt.		Slow	Fast
40YD 4M-1	6	4M13.0		80	y-y	Drop Weight 500 lb 6 in	0.030	L-W	None	1.62	0	NR	2.47	NR	8	0
2	6	"	"	"	"	500 lb 12 in	0.030	"	"	1.92	0	NR	4.09	NR	8	0
3	6	"	"	"	"	500 lb 24 in	NR	"	"	NR	0	NR	8.40	NR	8	0
4	6	"	"	"	"	500 lb 48 in	NR	"	"	NR	0	NR	16.6	NR	8	0
41YD 4M-1	6	"		"	"	500 lb 6 in	0.038	L-W A-S	Constant 8.75 ksi	1.15	0.24	NR	3.07	NR	8	0
2	6	"	"	"	"	500 lb 12 in	0.011	" "	Constant 7.09 ksi	1.68	0.19	NR	9.33	NR	8	0

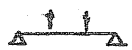
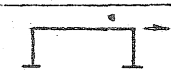
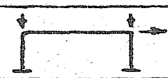
*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured (Maximum values listed): Axial Thrust T_m/T_e	Phenomena Measured (Maximum values listed): Load Point Accel., G's	Phenomena Measured (Maximum values listed): Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
20S 317.5	7	317.5		40	x-x	Incremental Deflection	Hours	L-HJ	None	2.21	0	NA	27	2.21	8	0
60S 317.5	7	"	"	136	"	"	"	"	"	1.29	0	NA	9.8	1.29	8	0
46D 317.5	7	"	"	80	"	Drop Weight Many Drops		L-W		(See NR	page 0	51) NA	NR	NR	3	0
47D 317.5	7	"	"	80	"	"		"		NR	0	NA	NR	NR	3	0
48D 317.5	7	"	"	60	"	"		"		NR	0	NA	NR	NR	3	0
49D 317.5	7	"	"	40	"	"		"		NR	0	NA	NR	NR	3	0
Frame 6	7	1/4 scl 6WF25		15	x-x	Rapid Loading	0.007	L-20^k	None	1.68	0	80	13.3	1.66	4	0
Frame 7	7	"	"	"	"	"	0.006	"	"	1.83	0	75	19.3	1.78	4	0
Frame 8	7	"	"	"	"	"	0.006	"	"	2.13	0	95	25.2	1.93	4	0
Frame 9	7	"	"	"	"	"	0.006	"	"	2.77	0	120	50.4	2.06	4	0

*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

Test Number	Reference*	Specimen Section Designation	Type of Specimen and End Restraint Conditions	Effective Simple Span Length, in.	Section Orientation	Lateral Load (Concentrated): Type of Loading or Deforming	Lateral Load (Concentrated): Time to Max. Lateral Load, Seconds	Lateral Load (Concentrated): Testing Machine Used	Axial Thrust: Type of Axial Thrust	Phenomena Measured (Maximum values listed): Lateral Load P_m/P_e	Phenomena Measured: Axial Thrust T_m/T_e	Phenomena Measured: Load Point Accel., g's	Phenomena Measured: Deflections x_m/x_e Ld. Pt.	Computed Lat. Ld. Resistance, Q_m/Q_e	Material Coupons Tested: Slow	Material Coupons Tested: Fast
Frame Beam 6	8	1/4 scl 6WF25		15	x-x	Incremental Deflection	Hours	L-C	None	2.1	0	NA	68	2.1	2	0
Frame Beam 7	8	"		NA	"	"	"	"	"	NR	0	NA	NR	NR	2	0
Frame Beam 12	8	"		15	"	"	"	"	"	2.2	0	NA	80	2.2	2	0
Frame M-1	8	"		NA	"	"	"	L-HJ	"	2.2	0	NA	57	2.2	8	0
Frame M-2.1	8	"	"	NA	"	Rapid Loading	0.007	L-20^k	"	1.69	0	80	7.6	1.8	8	0
Frame M-2.2	8	"	"	NA	"	"	0.007	"	"	2.04	0	90	18	2.15	8	0
Frame M-3.1	8	"	"	NA	"	"	0.007	"	"	1.90	0	90	12.6	2.0	8	0
Frame M-3.2	8	"	"	NA	"	"	0.007	"	"	2.32	0	120	29	2.35	8	0
Frame M-4	8	"	"	NA	"	"	0.006	"	"	2.51	0	NR	22	NR	8	0
Frame MA-1	8	"		NA	"	Incremental Deflection	Hours	L-HJ A-S	Constant 8.37 ksi	1.6	0.19	NA	58	1.6	8	0
Frame MA-2	8	"	"		"	Rapid Loading	0.007	L-20^k A-S	Constant 6.92 ksi	2.44	0.15	110	27.5	2.25	8	0

*References are listed at end of text

SUMMARY OF BEAM, BEAM-COLUMN, AND MODEL FRAME TESTS

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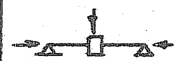
A-1	11	4M13.0		80	x-x	Slow Loading	120	L-60^k A-PJ	Constant 13.8 ksi	NR	0.37	NR	NR	NR	8	8
A-2	11	"	"	"	"	Rapid Loading	0.020	" "	Constant 10.5 ksi	1.32	0.28	51	3.4+	1.49	8	8
A-3	11	"	"	"	"	Slow Loading	90	" "	"	0.83	0.28	0	4.1+	0.83	8	0
A-4	11	"	"	"	"	"	510	" "	Constant 13.8 ksi	0.63	0.37	0	2.9+	0.63	8	0
A-5	11	"	"	"	"	Rapid Loading	0.018	" "	"	1.62	0.37	56	3.6+	0.97	8	8
B-1	11	"		"	"	Slow Loading	300	L-60^k	None	1.89	0	0	25.9	1.89	8	8
B-2	11	"	"	"	"	Rapid Loading	0.020	"	"	1.75	0	32	24.0	1.82	8	8
B-3	11	"	"	"	"	"	0.018	"	"	2.33	0	61	34.6	2.19	8	8
B-4	11	"	"	"	"	Incremental Deflection	1.25hr	L-HJ	"	1.58	0	0	23.4	1.58	8	0

*References are listed at end of text

+Determined just prior to specimen collapse